

Lepton pair production in heavy ion collisions and hadronic phenomenology

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Abstract

We first review the calculations of low invariant mass dilepton production in relativistic heavy ion collisions, using effective hadronic Lagrangians. We go through some of the theoretical techniques used in this kinematical region and we consider some of the appropriate experimental measurements. Moving up to the intermediate invariant mass region, we point out some of the uncertainties that show up in theoretical estimates. Those originate mainly from off-shell effects. Finally, as an application of hadronic chiral Lagrangians at finite temperature, we compute the mass shifts and mixing of the ω and ϕ mesons due to scattering from thermal pions.

Introduction

The field of heavy ion collisions is a very active one, straddling high energy and nuclear physics. At the upper energy limit of this flourishing area of research, the goal is to eventually produce and study a new state of matter in the laboratory: the quark-gluon plasma (QGP). That strongly interacting matter in conditions of extreme energy densities undergoes a phase transition is in fact a prediction of QCD [1]. To confirm whether the phase transition indeed occurs in relativistic heavy ion collisions and that the QGP is formed, one needs a clear signal as a signature for the QGP. Many approaches have been suggested to elucidate the existence of this elusive state of matter, but unfortunately, no single measurement can be singled-out as a “smoking gun” candidate. Instead, it appears that many complementary experimental data will require simultaneous analysis [2]. One class of observables

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that appears especially attractive is that of electromagnetic signals. This owes first to the fact that such probes essentially suffer little or no final state interactions and thus constitute reliable carriers able to report on the local conditions at their emission site. The calculated emission rates for photons and lepton pairs have been shown to strongly depend on the local density and temperature. Those facts were established some time ago and several heavy ion experiments specializing in the measurement of electromagnetic radiation are either running right now or being planned.

In this talk, we specialize on the topic of dilepton measurements and calculations. With respect to photons, the extra degree of freedom associated with a variable invariant mass constitutes an advantage that is clear when one considers annihilation reactions, for example. With this in mind, a pioneering experiment was that of the DLS [3], at the disassembled Bevalac at LBNL. Dileptons were also measured by the CERES [4] and HELIOS [5] collaborations at the SPS at CERN, and will be measured in the PHENIX experiment [6] at RHIC at BNL, and in the HADES experiment at GSI [7].

The emission of lepton pairs from high temperature matter formed in high energy nucleus–nucleus collisions is of great theoretical and experimental interest. It can signal a change in the properties of hadrons (more precisely, correlation functions) in hot hadronic matter as it approaches a chiral symmetry or a quark deconfinement phase transition or rapid crossover. Vector mesons are prominent in these studies because of their coupling to the electromagnetic current. Most studies have focussed on the lighter ones, ρ , ω , and ϕ , and on the heavier J/ψ . The best signals are those that have a characteristic shape or structure. The ρ meson is very broad in vacuum and undoubtedly gets even broader at finite temperature. The J/ψ is narrow; it has a whole literature of its own within the field. The ω and ϕ mesons are rather narrow, but not so narrow that they will all decay after the hot matter has blown apart in a high energy collision. This makes them good candidates to study.

The low mass region

In general, one can show that the rate for emitting a dilepton pair (or a real photon, for that matter) is related to the retarded photon self-energy, at finite temperature [8, 9]:

$$E_+ E_- \frac{dR}{d^3p_+ d^3p_-} = \frac{2e^2}{(2\pi)^6} \frac{1}{(k^2)^2} \left[p_+^\mu p_-^\nu + p_+^\nu p_-^\mu - g^{\mu\nu} p_+ \cdot p_- \right] \text{Im} \Pi_{\mu\nu}^R(k) \frac{1}{e^{\beta\omega} - 1}, \quad (1)$$

where the photon energy is ω , its three-momentum is \mathbf{k} , and $T = 1/\beta$.

A plausible philosophy then consists of performing an order-by-order loop expansion of the finite-temperature photon self-energy in the physical fields relevant for the problem at hand. One can then establish a correspondence between this approach and that consisting of simply using kinetic theory. It can be shown that

the difference in the dilepton rate between those two scenarios is indeed small up to reasonably high temperatures [9]. Systematic evaluation of this sort were carried out for the theoretical evaluation of real and virtual photon emission rates from a hot gas of mesons [10, 11]. We first concentrate on the rates for low mass dileptons and recall the assumptions inherent to most “first generation” estimates. We do not attempt to do justice to the many calculations in this area: we apologize in advance. In the following, we highlight some general aspects.

Having in mind the energy regime germane to the CERN SPS, a reasonable working hypothesis is to first assume that the hadronic medium is meson-dominated. This statement is experimentally supported [12]. Also, if thermal equilibrium is indeed established this would influence the soft sector. This defines a theoretical framework where finite-temperature hadronic field theory can be used to evaluate the photon self-energy. Its imaginary part can then be related to a dilepton emission rate. In practical reality, however, the above-mentioned connection with kinetic theory is in fact what is often used. Our “first generation” dilepton emission rate then contains the reactions and decays constructed from an ensemble of the lightest pseudoscalar (P) and vector mesons (V). Those are (P): π, η, η', K , and (V): ρ, ω, ϕ , and K^* . The processes included in our rate calculation are then: $V(P) \rightarrow P(V)\gamma^*$, $P + P \rightarrow \gamma^*$, $P + V \rightarrow \gamma^*$, and $V + V \rightarrow \gamma^*$. The respective sizes of those different contribution to the lepton spectrum are compared and discussed in Ref. [11] (see also Ref. [14]). Note that only two-body reactions were first considered, because of phase-space arguments. We shall return to this point later. Effective chiral Lagrangians were used in this calculation, coupled with Vector Meson Dominance [13] whenever experimental time-like form factors were unavailable.

A dynamical model is then needed to translate the rates into actual yields, effectively performing a space-time integration. The rates obtained by the procedure described above were integrated in a Bjorken model [14], and in an hydrodynamical model [15]. Running the results thus obtained through the detector acceptances, one can compare with the measured data. This has been done by several groups now, and the results are nicely summarized in Ref. [16]. Concentrating on the CERES invariant mass coverage, most calculations are seen to underestimate the data in the low mass sector ($M \approx 300$ MeV). One must nevertheless point out the remarkable agreement between the different theoretical estimates. The latter were obtained within different dynamical frameworks (see [16] and references therein for details) and this convergence of theoretical results has been claimed to show the insensitivity of the CERES results to dynamical modeling. Going back to our rates and recalling that those included many reaction channels (even though a few actually dominate), it appears that an independent verification of those estimates is desirable. In this context, we focus on two calculations. First, a calculation of photon and dilepton production rates from a gas of hot mesons was performed using chiral reduction formulæ and a virial expansion [17]. The results can be expressed in terms of vacuum current-current correlation functions, which can be experimentally constrained. Second, using spectral functions extracted from e^+e^- data one can thus

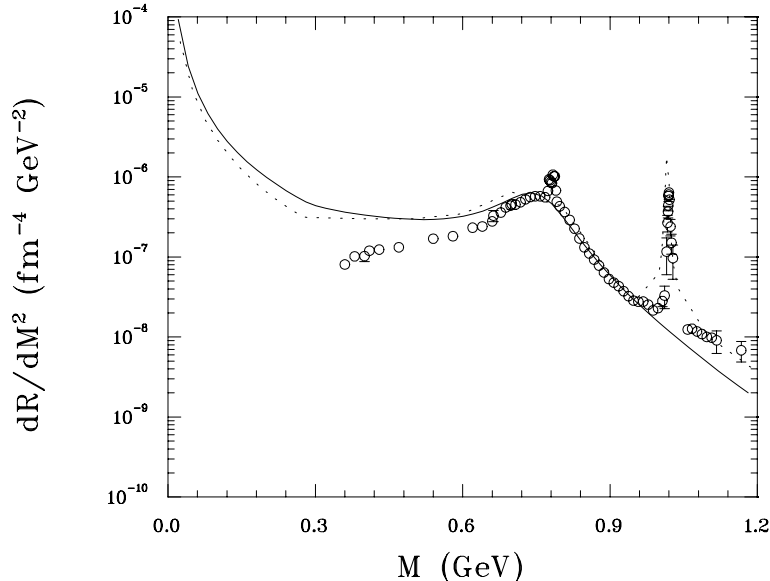


Figure 1: A comparison of the dilepton rates at $T = 150$ MeV calculated using experimentally-extracted spectral functions [18] (open circles), chiral reduction formulæ [17] (solid line), and meson reactions and decays [11] (dashed line).

calculate finite-temperature dilepton emission rates [18]. A comparison between the meson reactions/decays approach outlined earlier and those two calculations appears in Fig. 1. It is important to point out that Ref. [18] will not have the equivalent of the radiative decay channels, as the analysis is done starting from e^+e^- data. Strictly speaking, it will then be relevant just below the ρ pole, where the pion channels become large. Also, Ref. [17] does not have the ϕ in its formalism: this explains the absence of the peak. This being said, those three very different approaches exhibit striking agreement. Bear in mind that *no* arbitrary normalization enters *any* of those calculations. This is not to say that improvements can't be introduced but the unity of the displayed results is nevertheless satisfying.

Returning to the underestimation of the low mass data by the majority of the theoretical efforts, several alternative explanations have so far emerged. Since it is not the point of this talk to address this specific issue with the detail it deserves, we simply enumerate some of them. The early suggestion that the CERES data could be accounted for by a dropping of the in-medium ρ mass, has aroused immense theoretical interest. This conjecture can be incorporated in a model that fits the data [21]. Another line of reasoning consists of trying to make more complete dilepton rate assessments. This, combined with a kinetic theory constrained by the available data on spectral and multiplicity distributions, appears to be a step towards a resolution of the discrepancy [19]. Note that those rates will have to be reconciled with the alternate approaches described on Fig. 1. Finally, in-medium baryon effects on the ρ spectral function were shown to produce promising results, in connection with the

CERES measurements [20]. The last two schools of thought do not invoke dropping ρ masses. It is obviously too early to pin down the theoretical explanation which will stand the test of time. However, the community is eagerly awaiting the dilepton transverse momentum spectra which should help to discriminate between theories.

The intermediate mass region

Along with the tantalizing low-mass dilepton excess reported by CERES, an excess in the intermediate mass region ($m_\phi < M < m_{j/\psi}$) has also been seen [16]. Before attempting to make phenomenological estimates, it is best to exercise caution and to tackle this issue purely theoretically. It has been shown in the past that, right past its threshold, the reaction $\pi + a_1 \rightarrow e^+e^-$ constituted a sizeable fraction of the lepton pair spectrum [22]. This exercise was carried out using an effective chiral Lagrangian. However, the procedure to derive those is unfortunately not unique [23]. Now, because we are no longer in the soft sector, our concern is that the non-uniqueness of the available chiral Lagrangians will manifest itself, principally through off-shell effects. With this in mind, we report here on our findings only briefly, leaving a more detailed discussion to be published [24].

Here, we therefore carry out a mostly pedagogical exercise: what are the sizes of the possible off-shell effects inherent to effective Lagrangians, when used to calculate lepton pair production? The definite example we have in mind is again $\pi + a_1 \rightarrow e^+e^-$, evaluated with the help of VMD. We are therefore concerned by the different possible manifestations of $\mathcal{L}_{\pi\rho a_1}$. The source of our concern is illustrated as follows. The most general vertex for $a_1 \rightarrow \pi\rho$ decay can be written as

$$\Gamma^{\mu\nu} = ig_1 g^{\mu\nu} + ig_2 p^\mu k^\nu + ig_3 p^\nu k^\mu + ig_4 p^\mu p^\nu + ig_5 k^\mu k^\nu, \quad (2)$$

where $g_i(p^2, k^2)$ is a form factor, with p^μ and k^ν being the a_1 and ρ four-momenta. For on-shell a_1 decay, three of the above terms are identically zero, leaving only two. The form factors are then chosen such that the experimental width, $\Gamma_{a_1 \rightarrow \pi\rho}$, is reproduced. The extra experimental constraint is then the ratio of D to S wave in the final state, which is measured experimentally [25]. It is probably fair to say that the importance of this hadronic constraint has not quite penetrated the heavy ion community, as revealed by a literature survey. When using the above vertex for dilepton production, the virtual ρ is pushed off-shell and one has no direct control over such extrapolations. It turns out that for the case at hand, the uncertainty actually resides in the form factors [24]. We calculate the dilepton rate from the reaction above with: **(1)** an effective chiral Lagrangian constructed by Ko and Rudaz based on the $SU(2)_L \times SU(2)_R$ linear σ model [26]; **(2)** an effective chiral Lagrangian where the vector mesons are introduced as massive Yang-Mills fields of the chiral symmetry [22]; **(3)** an effective Lagrangian, previously used by Xiong, Shuryak and Brown [27] in connection with photon emission rates; **(4)** an effective Lagrangian developed by Janssen, Holinde, and Speth [28], to address the issue of form factors

in the Bonn potential. The dilepton rates evaluated with those interactions are displayed in Fig. 2.

The first striking feature of this plot is that the dilepton rates span three orders of magnitude. Off-shell effects are indeed important, as also pointed out by a calculation done along similar lines [29]. For additional help, we can however rely on the rates calculated through the experimentally-extracted spectral functions [18] used previously. The $\pi + a_1$ reaction should be a large (if not the largest) contributor to the dilepton signal in the invariant mass region of interest. With the available information we can start our examination of the models. Table 1 summarizes their empirical predictions, along with the actually measured quantities. Parameter set I for the interaction of Ko *et al.* is taken from Ref. [29]. Concerning the observables in Table 1, this parameter set does not actually represent the lowest χ^2 : parameter set II satisfies this criterion. It is interesting to notice that a modest variation in χ^2 for the fit of the on-shell empirical observables translates into a large variation of the predicted dilepton rate. Fig. 2 also contains the rate deduced from the experimentally-fitted spectral functions [18]. Because the process discussed here is actually included in the spectral function analysis along with other channels (which are known to interfere constructively), the open circles represent a strong upper limit for the calculations discussed here. This upper bound is strongly

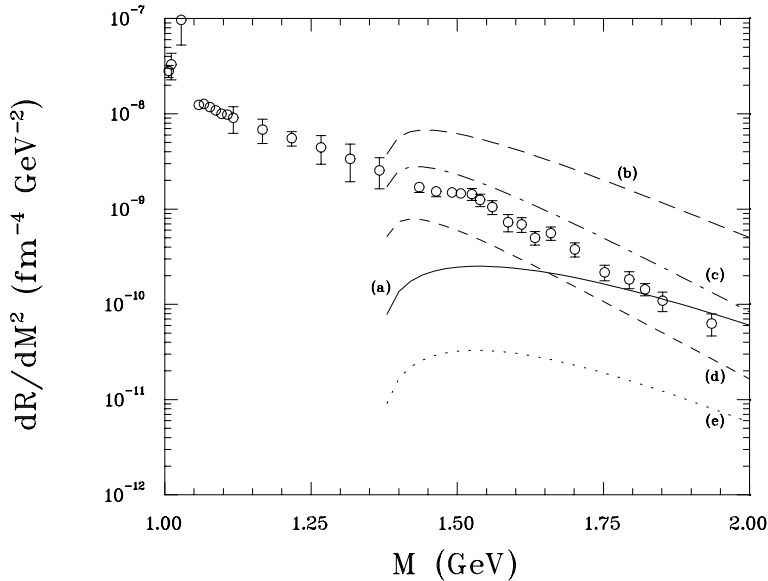


Figure 2: Production rates for intermediate invariant mass dileptons calculated at $T = 150$ MeV using the following interactions: **(a)** and **(b)** Ko and Rudaz's chiral Lagrangian [26] (the difference between **(a)** and **(b)** is explained in the main text); **(c)** the effective chiral Lagrangian used by Song, Ko, and Gale [22]; **(d)** Lagrangian of Janssen, Holinde, and Speth [28]; **(e)** Lagrangian used by Xiong, Brown, Shuryak [27]. Also shown is the rate calculated from experimentally-fitted spectral functions [18] (open circles).

	Ko <i>et al.</i>		Song <i>et al.</i>	Xiong <i>et al.</i>	Janssen <i>et al.</i>	DATA
	I	II				
$\Gamma(a_1\rho\pi)$	313.4	579.1	400	400	400	~ 400 MeV
$\Gamma(a_1\pi\gamma)$	0.572	1.171	2.819	1.940	0.312	0.640 ± 0.246 MeV
D/S	0.078	-0.168	-0.099	0.185	0.045	-0.09 ± 0.03 MeV
χ^2	11.2	9.8	39.3	37.3	11.0	

Table 1: The phenomenology of different models.

violated by our parameter set II for the Lagrangian of Ref. [29]. To a lesser extent this is also the case for the results of calculations with the interaction of Ref. [22]. In the remaining models in Table 1, the lowest χ^2 is obtained with the Lagrangian of Ref. [28]. Parameter set I of Ko *et al.* has as good a χ^2 , but the slope of the dilepton spectrum departs considerably from that of the spectral function analysis, with a violation of the upper bound just below $M = 2$ GeV. The Lagrangian of Xiong *et al.* produces a high χ^2 , with a much flatter slope. We could deem here the interaction of Janssen *et al.* to be the most satisfactory. It can also be made to saturate the spectral function curve with a proper choice of form factors, without spoiling its on-shell properties. However, the spectral function analysis can be made to be specific to the πa_1 channel and the qualitative aspects discussed here can be set on a quantitative footing; we stick here to our pedagogical goal and postpone this discussion [24].

It is clear which caveats will then await us when we embark on the phenomenological analysis of the experimental data. The purpose of this exercise was to show that using all of the available empirical constraints, one could indeed restore some certainty to an apparently ambiguous situation. There are thus reasons to be optimistic about this type of analyses. The experimentally-extracted spectral function prove to be helpful, and serve here as baseline calculations. Then, the effective Lagrangian theory can be used to extrapolate into the realm of finite-temperature and many-body effects.

$\omega - \phi$ mixing at finite temperature

A last application of effective hadronic Lagrangians will cover here the mixing of the ω and ϕ vector mesons. In vacuum the ϕ meson is almost entirely $\bar{s}s$ in its valence quark content while the ω meson is almost entirely nonstrange. There is a small mixing as evidenced by the observed decay mode $\phi \rightarrow \pi\rho$ and by previous studies using effective hadronic Lagrangians. We will study the change in masses and mixing angles of the ω and ϕ at moderate temperatures using only conventional ideas. We consider our study a simple extrapolation of known physics which may help in deciphering future experiments. Specifically, we study the scattering of these

mesons from thermal pions which are the most abundant mesons at temperatures below 100 MeV or so. We use effective Lagrangian techniques to model the relatively soft interactions coupling pions, ω , and ϕ mesons, fitting the parameters to known physical quantities. The resulting scattering amplitudes are used in a virial expansion to compute the vector meson properties at finite temperature.

A survey of the literature on effective hadronic Lagrangians and the Review of Particle Physics [30] suggests that the interactions of relevance involve the 3-point vertices $\phi\rho\pi$, $\omega\rho\pi$, $\phi b_1\pi$, and $\omega b_1\pi$. The vector self-energies are obtained by computing one loop diagrams at finite temperature [38]. The interaction involving the ρ meson is described by the Wess–Zumino term [32].

$$\mathcal{L}_{(\omega,\phi)\rho\pi} = g \epsilon^{\alpha\beta\mu\nu} \partial_\alpha \rho_\beta \cdot \pi \left(\frac{\partial_\mu \omega_\nu^8 + \sqrt{2} \partial_\mu \omega_\nu^s}{\sqrt{3}} \right) \quad (3)$$

The octet and singlet fields, ω_8 and ω_s , are expressed in terms of the (vacuum) physical fields with a mixing angle θ_V .

$$\begin{aligned} \omega_8 &= \phi \cos \theta_V + \omega \sin \theta_V \\ \omega_s &= \omega \cos \theta_V - \phi \sin \theta_V \end{aligned} \quad (4)$$

Ideal mixing is defined such that the physical ϕ meson would not couple to non-strange hadrons. This corresponds to $\theta_V = \theta_{\text{ideal}} = \tan^{-1}(1/\sqrt{2}) \approx 35.3^\circ$. The real world is not far from that. Durso [33], for example, fits 39.2° , while the Review of Particle Physics quotes 39° based on the Gell–Mann Okubo mass formula. The coupling constant g is related to the coupling g_{VVP} used by Gomm, Kaymakçalan, and Schechter [34] by $g = -\sqrt{2} g_{VVP}$. Durso fits $g^2 = 1.62 \pm 0.19 \times 10^{-4} \text{ MeV}^{-2}$ with a pseudoscalar mixing angle $\theta_P = -9.7^\circ$. We will insure that our parameters reproduce the $\phi \rightarrow \rho\pi$ decay rate. Accepting Durso’s value of g we fit $\theta_V = 40.1^\circ$.

The $b_1(1235)$ has a branching ratio of more than 50% into $\omega\pi$ and less than 1.5% into $\phi\pi$. Thus, the b_1 meson is important for the mass shift of the ω meson at finite temperature, as noticed by Shuryak [35]. The interactions are assumed to be SU(3) symmetric with SU(3) broken only by mass terms. The Lagrangian is [38]

$$\mathcal{L}_{(\omega,\phi)b_1\pi} = g_{b_1} \pi \cdot \mathbf{b}^\mu \left(\frac{\omega_\mu^8 + \sqrt{2} \omega_\mu^s}{\sqrt{3}} \right) + h_{b_1} \pi \cdot \mathbf{b}^{\mu\nu} \left(\frac{\omega_{\mu\nu}^8 + \sqrt{2} \omega_{\mu\nu}^s}{\sqrt{3}} \right). \quad (5)$$

The two coupling constants can be inferred from the decay rate $b_1 \rightarrow \omega\pi$ and from the ratio of the D wave content of the decay amplitude to its S wave content. The Review of Particle Physics gives the width $142 \pm 8 \text{ MeV}$ and the measured D/S ratio 0.26 ± 0.04 . Fitting to central values determines the most likely values of the coupling constants to be $g_{b_1} = -9.471 \text{ GeV}$ and $h_{b_1} = 6.642 \text{ GeV}^{-1}$.

The location of the poles and the mixing angle at finite temperature are obtained by finding the zeros of the inverse propagator in the (vacuum) physical ω – ϕ basis.

$$\mathcal{D}^{-1}(k_0, \mathbf{k}) = k_0^2 - \mathbf{k}^2 - M^2 - \Sigma(k_0, \mathbf{k}) \quad (6)$$

M^2 is the 2×2 mass matrix at zero temperature. It is diagonal with components $M_{11}^2 = m_\omega^2$ and $M_{22}^2 = m_\phi^2$. The self-energy has contributions from the ρ meson and from the b_1 meson. The first was calculated by Haglin and Gale [36]. The second is readily calculated by the usual finite-temperature rules [37]. We restrict our attention to the finite-temperature contribution. We consider only ω and ϕ mesons at rest in the many-body system ($\mathbf{k} = 0$) since that is where temperature will have its maximum impact. As $|\mathbf{k}|$ increases, many-body effects will decrease, and in the limit $|\mathbf{k}| \gg T$ they will disappear altogether. Finally, the imaginary part of the self-energy is small compared to the real part (inclusive of M^2) and so we do not include it in our present calculation. We find

$$\Sigma(k_0, |\mathbf{k}| = 0) = \begin{pmatrix} \cos^2 \delta_V & -(\cos \delta_V \sin \delta_V)/2 \\ -(\cos \delta_V \sin \delta_V)/2 & \sin^2 \delta_V \end{pmatrix} (\Sigma_\rho + \Sigma_{b_1}), \quad (7)$$

where $\delta_V = \theta_V - \theta_{\text{ideal}}$ measures the deviation from ideal mixing. The scalar functions

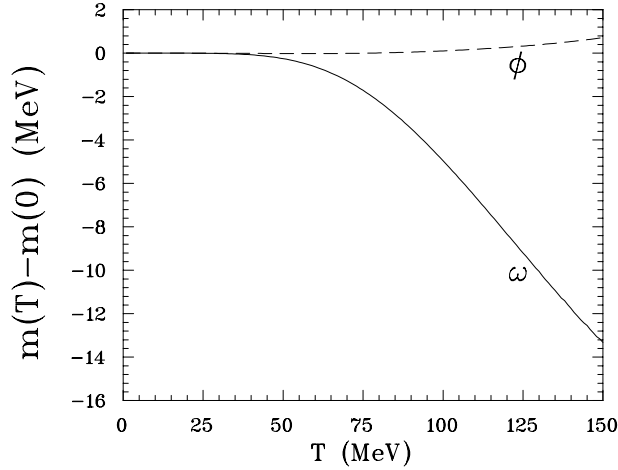


Figure 3: Mass shifts of the ω and ϕ mesons as functions of temperature due to scattering from thermal pions. Multiple pion scattering and scattering from other thermal mesons should become important above 100 MeV temperature.

Σ_ρ and Σ_{b_1} are given in Ref. [38].

After diagonalization one finds the mass shifts as functions of the temperature. They are displayed in Fig. 3. Although the results are plotted up to a temperature of 150 MeV to see the effect, other scattering processes will come into play above 100 MeV, as mentioned earlier. The ω mass goes down and a shift of roughly 13 MeV is reached at a temperature of 140 MeV. The ϕ mass increases monotonically to about 0.6 MeV above its vacuum value at a temperature of 140 MeV. The mixing angles remain uninterestingly small at all temperatures [38], but the mass shift of the ω is potentially detectable in future experiments.

Conclusion

In conclusion, in our brief description of calculations for the low mass sector we have shown agreement between different theoretical approaches to dilepton rate calculations. At higher invariant masses, the considerable uncertainties associated with off-shell effects have been confirmed. Nevertheless, we argue that the available phenomenology helps considerably in narrowing down the possibilities. Finally, we compute the finite-temperature change in the masses of the ω and ϕ mesons and their mixing angle.

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